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Electron density and temperature measurements in the cold plasma environment of Titan: Implications for atmospheric escape

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[1] We present electron temperature and density measurements of Titan's cold ionospheric plasma from the Langmuir probe instrument on Cassini from 52 flybys. An expression of the density as a function of temperature is presented for altitudes below two Titan radii. The density falls off exponentially with increased temperature as $\log(n_e) = -2.0\log(T_e) + 0.6$ on average around Titan. We show that this relation varies with location around Titan as well as with the solar illumination direction. Significant heating of the electrons appears to take place on the night/wake side of Titan as the density-temperature relation is less steep there. Furthermore, we show that the magnetospheric ram pressure is not balanced by the thermal and magnetic pressure in the topside ionosphere and discuss its implications for plasma escape. The cold ionospheric plasma of Titan extends to higher altitudes in the wake region, indicating the loss of atmosphere down the induced magnetospheric tail. **Citation:** Edberg, N. J. T., J.-E. Wahlund, K. Ågren, M. W. Morooka, R. Modolo, C. Bertucci, and M. K. Dougherty (2010), Electron density and temperature measurements in the cold plasma environment of Titan: Implications for atmospheric escape, *Geophys. Res. Lett.*, 37, L20105, doi:10.1029/2010GL044544.

1. Introduction

[2] Titan was first visited by the Voyager 1 spacecraft in 1980, which conducted a single flyby of the moon. It was empirically shown that Titan had an ionosphere [Bird *et al.*, 1997] and that an induced magnetosphere was formed around the body [Ness *et al.*, 1982]. Titan was found to orbit Saturn within the Saturnian magnetosphere, such that a complex electromagnetic interaction was expected to take place between Titan's ionosphere and Saturn's co-rotating plasma.

[3] In 2004, Cassini started performing flybys of Titan and the knowledge has grown significantly ever since. It was determined that Titan does not have any strong intrinsic magnetic field of its own. The ionosphere therefore interacts directly with the ambient plasma flow [Backes *et al.*, 2005]. The ionosphere was found to be populated mainly by HCNH^+ and C_2H_5^+ ions but with a wealth of additional species

[Cravens *et al.*, 2006]. Wahlund *et al.* [2005] reported that Saturn's magnetospheric conditions affected the structure and dynamics of the deep ionosphere of Titan. Modolo *et al.* [2007] subsequently showed that the wake region of the induced magnetosphere of Titan could be very asymmetric due to a non-ideal upstream flow direction. Ågren *et al.* [2007, 2009] studied the deep ionosphere and showed that magnetospheric impact ionization played a role in the formation of the ionosphere but that the solar extreme ultraviolet radiation was the main ionization source on the dayside. Cravens *et al.* [2008] argued that magnetospheric impacts strongly contributed to the ionization in the altitude range 500–1000 km. On the nightside, plasma transport from the dayside could be a strong contributor to the ionospheric content [Cui *et al.*, 2009].

[4] As Titan orbits Saturn, the incident angle between the co-rotation flow direction and the Sun-Titan direction will vary with orbital phase, creating a complex ionosphere-magnetosphere interaction. Furthermore, Rymer *et al.* [2009] showed that the surrounding plasma of Titan can typically be categorized into being magnetosheath, lobe-like, plasma sheet or bimodal. This extreme variability of the surrounding environment causes variability in Titan's plasma environment and possibly to the intensity of escaping cold plasma. Even though the vast majority of the cold plasma around Titan can be found in the ionosphere, fractions also escape the moon and is being transported downstream [Wahlund *et al.*, 2005; Modolo *et al.*, 2007]. The escape does not appear to occur at a steady pace. Coates *et al.* [2007] reported that an enhanced escape rate of ionospheric plasma took place when the ambient magnetospheric dynamic ram pressure was enhanced. Cui *et al.* [2010] provided measurements of how the ion transport at Titan has a strong diurnal variation. Wei *et al.* [2007] argued that cold plasma observed in the tail region was moving along flux tubes with one end connected in the deep ionosphere of Titan and that particles could travel along the field lines away from the ionosphere.

[5] In this paper, we will present result from a statistical study of the Langmuir probe measured electron density and temperature and thermal pressure at Titan and how those properties vary with Titan's orbital phase and location around the moon.

2. Instrumentation

[6] The Cassini spacecraft carries the radio and plasma wave science (RPWS) instrumentation consisting of three electric field sensors, three magnetic field sensors, a spherical Langmuir probe and three receivers; high, medium and wideband [Gurnett *et al.*, 2004]. In this study we have used

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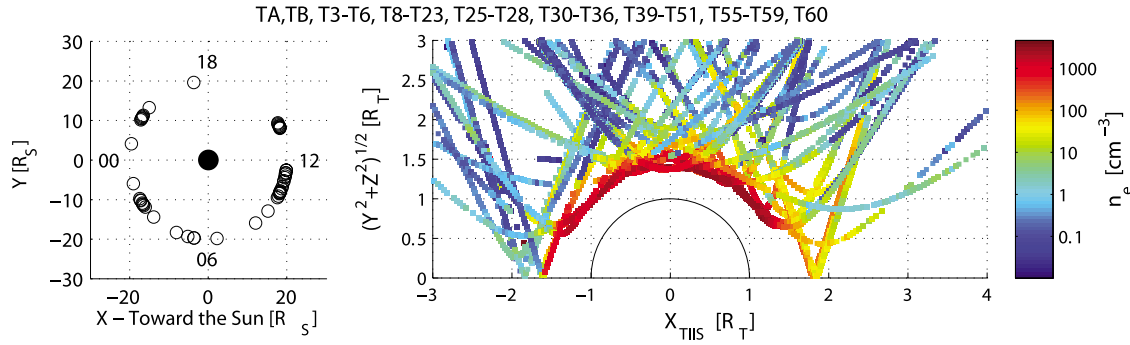


Figure 1. (left) The position of Titan relative to Saturn during the 52 Cassini flybys listed at the top of the figure and, (right) the Langmuir probe measured electron density along the spacecraft track in cylindrical TIIS coordinates.

data from the Langmuir probe, but also compared those density measurements to the ones from the 10 m antenna, which provides an independent density measure through detection of the upper hybrid frequency line. During a Titan flyby the Langmuir probe is usually run in a sweep mode when the bias voltage fed to the probe sweeps from -4V to $+4\text{V}$ (when a flyby does not reach below 1400 km the probe normally sweeps from -32V to $+32\text{V}$) and collects an ion and electron current. Such a sweep is carried out every 24 s. From the voltage-current characteristics it is possible to derive bulk parameters of the plasma, such as electron density n_e and temperature T_e . For a more thorough description of the Langmuir probe measurements and capabilities at Titan we refer to *Wahlund et al.* [2005, 2009] and *Ågren et al.* [2009]. Cassini also carries the magnetic field instrument (MAG) which provides vector magnetic field measurements [*Dougherty et al.*, 2004], from which we use 1 min averaged data of the magnetic field strength.

3. Observations

[7] In this study, we have included 52 Titan flybys (104 altitude profiles) during which the Langmuir probe operated in sweep mode. The selected flybys are listed above

Figure 1. Figure 1 (left) shows the position of Titan relative to Saturn during the flybys. The right panel shows the electron density measured by the Langmuir probe along the track of Cassini in cylindrical coordinates in the Titan interaction coordinate system (TIIS). In the TIIS system the x axis is directed along the ideal flow vector of Saturn's co-rotating plasma, the y axis is in the direction of Saturn and the z axis completes the right-handed system. The flybys are spread evenly around Titan and most of them take place at roughly 02h, 10h, 14h and 22h Saturn local time (SLT). They cover both the ram side and the wake side of the interaction region with Saturn's co-rotating magnetosphere as well as the night side and the day side of Titan.

3.1. Altitude Profiles

[8] Using the Langmuir probe measurements we can show how the electron density and temperature behave in the near Titan space. The altitude profiles of the electron density and of the electron temperature for all used flybys are shown in Figures 2a and 2b. It should be mentioned that the exo-ionopause, the boundary between Titan's plasma and the surrounding magnetospheric plasma, is not really visible in our average altitude profiles. If plotting single flyby density-altitude profiles then this boundary can usually be

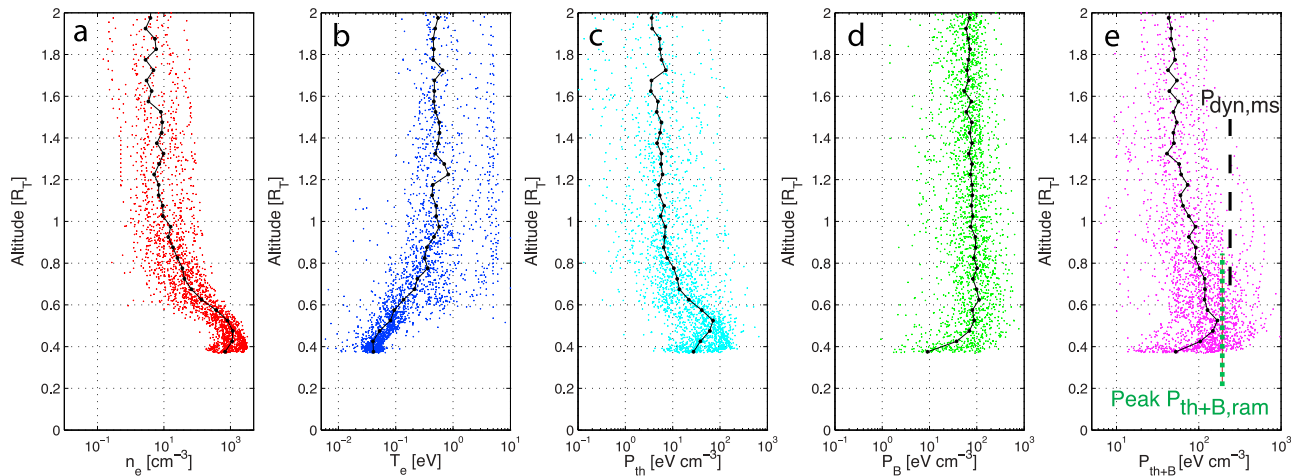


Figure 2. Combined observed altitude profiles of (a) the electron density, (b) the electron temperature, (c) the thermal pressure, (d) the magnetic pressure and (e) thermal plus magnetic pressure. The black solid lines show the median values. The black dashed line in Figure 2e shows the approximate magnetospheric ram pressure and the green dotted line shows the average peak pressure when only including ram side data.

observed in the altitude range 0.6–2 R_T (1 R_T = 2575 km). Below 1–2 R_T the thermal pressure $P = n_e k_B T_e$ starts to increase with decreasing altitude, as is shown in Figure 2c, while Figure 2d shows the magnetic pressure $P_B = B^2/2\mu_0$ and Figure 2e shows the sum of the magnetic and thermal pressure. The magnetic pressure is generally the dominant pressure source of the two above the exobase ($\sim 0.6 R_T$). The average magnetospheric dynamic ram pressure $P_{dyn,ms} = \rho v_{ms}^2$, where $\rho = n_{ms} m_{ms}$ is the mass density, is indicated by the black dashed vertical line and is calculated by assuming a density $n_{ms} = 0.1 \text{ cm}^{-3}$, a speed $v_{ms} = 120 \text{ km s}^{-1}$ and that the main constituent in the magnetosphere is O^+ with mass $m_{ms} = 16 \text{ amu}$. The average peak pressure (thermal + magnetic) when only including ram side data is indicated by the green dotted line. We can see from Figure 2e that the sum of the magnetic and thermal pressure at the peak on the ram side is on average somewhat less than the assumed ambient magnetospheric dynamic ram pressure (190 eV cm^{-3} compared to 240 eV cm^{-3}). This result shows that the thermal and magnetic pressures alone are not enough to balance the upstream pressure and that other pressure sources are needed in Titan's topside ionosphere.

3.2. Electron-Temperature Relation

[9] Using the same measurements as in section 3.1 we can present, in Figure 3a, the electron density as a function of temperature, color-coded by altitude. This shows that there is a clear trend of how the density decreases with increasing temperature and increasing altitude. This trend is visible up to an altitude of $\sim 2 R_T$ where the transition region from ionospheric plasma of Titan to the magnetospheric plasma of Saturn is usually located. A least-squares fit to the data points below 2 R_T has a slope of -2.0 and a coefficient of determination $R^2 = 0.53$.

[10] Furthermore, in Figures 3b–3e we present the same Langmuir probe data again but now divided into four panels according to whether the measurements take place on the day side or on the night side of Titan as well as on the ram side or on the wake side. Night/day side here means that the solar zenith angle is larger/smaller than 100° (not 90° since Ågren *et al.* [2009] showed that solar ionization is important even beyond the terminator) and wake/ram side means the TIIS x coordinate is larger/smaller than 0. The fits are only including data from below 2 R_T . We can see that there are significant differences in the observed profiles between each subplot. The slopes are generally steeper on the day side than on the night side (-2.5 and -2.6 compared to -1.7 and -1.3): the electron density falls off slower with increasing temperature on the night side of Titan. This result indicates that there could be electron heating mechanisms in play on the night side.

[11] We have also tried to divide the data into the categorization of Rymer *et al.* [2009], but found no significant difference between each category. If only including Titan flybys during plasma sheet conditions (where most flybys occur) then similar trends as presented in Figure 3 for the four geometrical locations still arise.

4. Discussion

[12] We have shown that the electron density and electron temperature measured by the Langmuir probe in Titan's upper atmosphere are strongly related. We have presented

statistical results on the thermal pressure in comparison to the magnetic pressure.

[13] The electron density has been shown empirically to decrease exponentially with increasing electron temperature as

$$\log(n_e) = -2.0 \log(T_e) + 0.6, \quad (1)$$

which implies that

$$T_e \propto n_e^{\gamma-1}, \quad (2)$$

where the polytropic index $\gamma = 0.5$. This relation is generally valid up to $\sim 2 R_T$ above the surface of Titan. This anti-correlation clearly shows that the plasma around Titan does not expand adiabatically since an exponential correlation would then be observed with $1 < \gamma < 2$. The anti-correlation is due to that the available energy is shared among more electrons, as the altitude decreases.

[14] The density-temperature relation is found to change with location around Titan relative to the direction to the Sun and the direction of the ideal co-rotational flow. A prominent difference is that the slope of the curve is steeper on the day side compared to on the night side. The density falls off faster with increasing temperature on the day side. This could indicate the presence of surplus particle heating mechanisms on the night side. The heating begins above the exobase and could be due to wave-particle interactions, parallel electric field acceleration or heat flow from above, for instance. Coates *et al.* [2007] suggested that ambi-polar electric fields were set up in the wake side when photoelectrons, being more energetic than ions, escape Titan, which could also be a likely explanation for our findings of heating on the night side. They argued that this would enhance pressure driven escape.

[15] There are a few stray points at extreme density and temperature values which might be measurement errors, and there is a mixture of photoelectrons in the data with densities below $\sim 5 \text{ cm}^{-3}$. Still, there are larger populations of ionospheric origin that stand out. On the night side (Figures 3d and 3e) there are prominent populations within 2–10 eV and $0.3\text{--}50 \text{ cm}^{-3}$ and below 2 R_T where the electron temperature is higher than elsewhere, suggesting that significant electron heating can take place there. In the wake side (Figures 3c and 3e) there are populations around 1 eV and 100 cm^{-3} with again higher temperatures indicating active heating. High plasma densities are observed farther out on the wake side than on the ram side (see Figure 1) which supports the idea of outflow of cold ionospheric plasma through the tail of Titan.

[16] In this study, the thermal pressure has been shown to decrease rapidly with increasing altitude above the ionospheric peak altitude at $\sim 0.5 R_T$, while the magnetic pressure is, on average, more constant with altitude around Titan. The magnetic pressure shows a similar decreasing trend with increasing altitude when only including ram side data, due to the pile up in front of the moon. If comparing our results to MHD simulations by Ma *et al.* [2006] we see that we get a factor ~ 3 lower peak pressure than their simulations. However, they did in fact use an upstream density of 0.3 cm^{-3} which could be an explanation for the discrepancy. It is also noteworthy that their simulations do not show any peak in the thermal pressure as is clearly seen in our study at $0.5 R_T$.

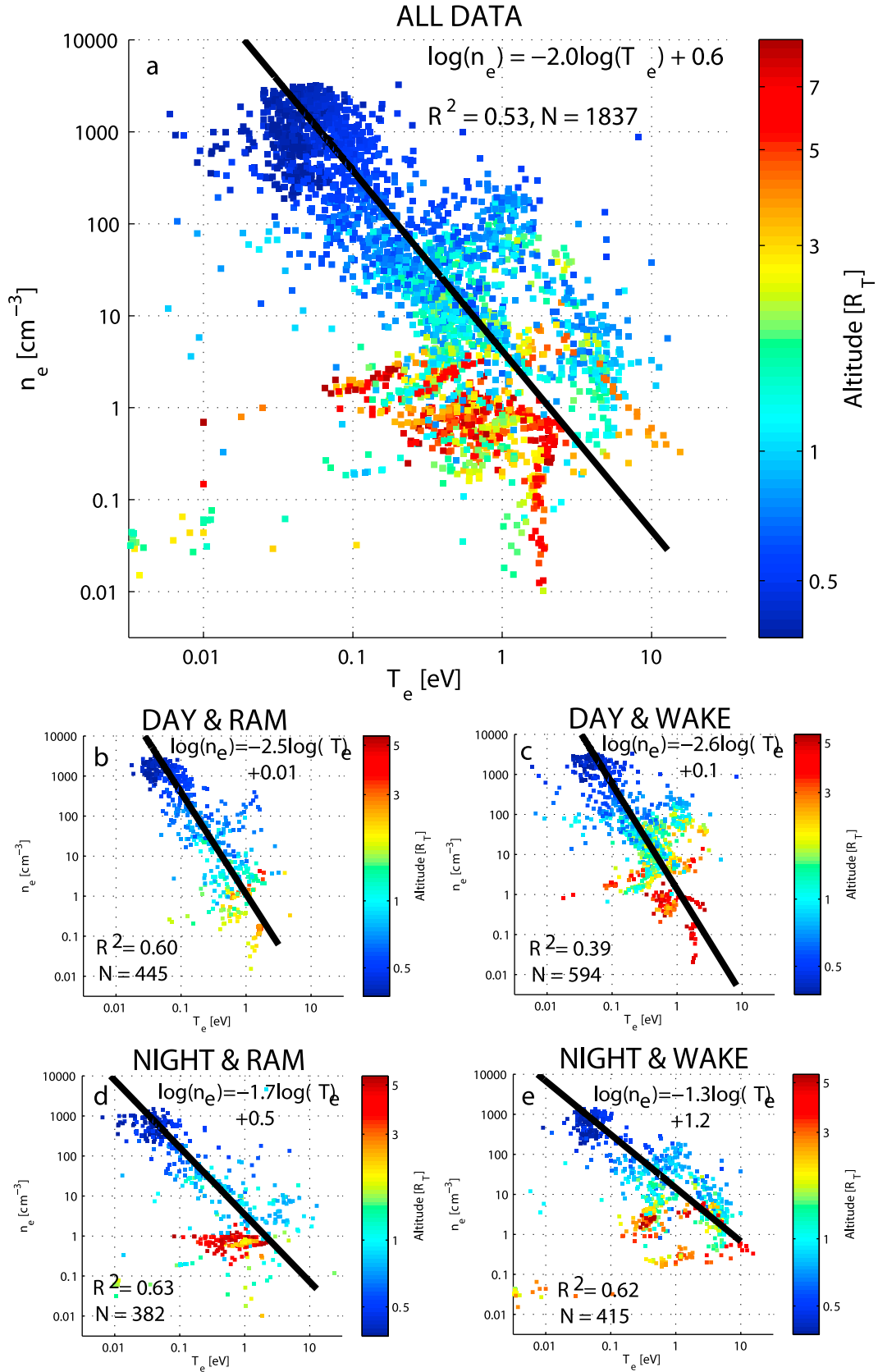


Figure 3. (a) Electron density plotted as a function of electron temperature and color-coded by altitude with data from all included flybys. (b–e) The same data as in panel a but subdivided into ram or wake side of Titan and night side or day side, as indicated at the top of each panel. The least-squares fit only includes data from below 2 R_T and the expression of the curve is given in each panel together with the coefficient of determination (R^2) and the number of datapoints (N).

As we see a decrease in the sum of the thermal and magnetic pressure, a resulting increase in dynamic pressure of the ionospheric plasma should hence be present in order to maintain a pressure balance. This implies that ionospheric plasma is set in motion on a regular basis at Titan.

[17] We have not considered the upstream energetic particle pressure which would add even more to the upstream pressure [Garnier *et al.*, 2009]. In the topside ionosphere, since no pressure balance is reached, plasma will be set in motion due to the forced increase of the dynamic pressure. The total pressure (magnetic plus thermal) is generally higher on the ram side than on the wake side which implies transport to the wake side. It is also important to consider the role of collisions, which could be a main factor that prevents most of the ionospheric plasma from escaping Titan. Collisions only start to become important in the dense plasma below the exobase.

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